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DESIGN PROGRESS AT THE NATIONAL ACCELERATOR LABORATORY 1968 - 1969

M. S. Livingston

June 30, 1969

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ABSTRACT

The purpose of this report is to describe for the historical record the continuing changes in design of the 200-GeV accelerator and its associated facilities.

*This work was done under the auspices of the U. S. Atomic Energy Commission.

A. INTRODUCTION

The initial design of the 200-GeV accelerator and its associated facilities was prepared during the summer and fall of 1967 and was presented in the Design Report[1] of January 1968. This Report was submitted to the United States Atomic Energy Commission along with a proposal for construction and became the basis for Congressional authorization of the design program and start of construction at the National Accelerator Laboratory. The early history of the NAL, and the origins of the concepts presented in the Design Report, are described in an NAL report[2] written in the spring of 1968.

The conceptual design proposed in the Design Report was known to be preliminary. Much further study and many revisions were anticipated to prepare adequate specifications for construction. Such studies and revisions have been in process continuously since submission of the Report, covering essentially all features and components of the accelerator facility. In some instances they have resulted in significant changes; in others, the original plans and parameters have been retained.

The intent of this report is to describe the various studies qualitatively, with emphasis on the reasons leading either to revision or retention of the original concepts. Changes in the technical parameters are available elsewhere. Some specific changes are included in a second printing of the Design Report[1a] issued in July 1968. Others are presented in laboratory notes or memoranda (references are given), or are described qualitatively in the official Monthly Reports[3] to the AEC. A few have not yet been documented in technical reports but are recorded in design drawings or in minutes of section meetings. These challenges to or changes in the original designs, and the arguments which justify them, are presented under individual topic headings in the sections to follow. For completeness, other developments in site and facilities planning are included.

B. LABORATORY AND SITE DEVELOPMENT

1. Organization and Staff

The initial roster of scientists and engineers assembled by the Director at Oak Brook in the summer of 1967 to prepare the conceptual design consisted of many individual experts in one or more aspects of accelerator planning and design.[2] They concentrated as individuals or in small groups on specific design planning and calculations and acted as a committee-of-the whole in discussions of basic design concepts. General meetings were held almost every day to discuss progress and guide decisions. The only organizational subdivisions were those following from the specializations of the individuals.

During the summer and fall of 1967 the Director enlisted staff for the NAL, and as they arrived certain experienced members were assigned specific responsibilities, following a natural breakdown of the accelerator complex into its several components and functions. Eight sections were recognized and activated at an early date, and individuals were assigned to lead the sections. These were:

Accelerator Theory - L. C. Teng
Linac - D. E. Young
Booster - A. van Steenbergen (later R. Billinge, Act.,
P. J. Reardon)
Main Accelerator - J. W. DeWire (later F. C. Shoemaker)
Radio Frequency - Q. A. Kerns
Beam Transfer - A. W. Maschke
Radiation Physics - M. Awschalom
Experimental Facilities - A. L. Read, Act., J. R. Sanford

The first six sections above composed an Accelerator Division, of which R. R. Wilson acted as Director and T. L. Collins was Associate Director. A Research Division under E. L. Goldwasser, Deputy Director, initially had two sections--Radiation Physics and Experimental Facilities. M. S. Livingston, Associate Director, served as Staff Advisor to the Director. Administrative functions were headed by D. R. Getz, Assistant Director; D. K. Poillon was Business Manager. F. T. Cole, Assistant Director, supervised laboratory publications and edited the Design Report. Collins was given responsibility for liaison with the DUSAF architect/engineers. During this period the laboratory did not have a formal organization; many persons had overlapping interests and activities. Frequent group discussions of basic design features continued.

During 1968 and early 1969 the laboratory staff increased at an accelerating rate, stimulated by the move from the Oak Brook quarters to the design site in the former village of Weston. Personnel records show the following numbers of professional and total staff on the NAL roles:

Date	Scientists/Engineers	Total Staff
Jan. 1, 1968	26	90
April 1, 1968	47	132
July 1, 1968	54	200
Oct. 1, 1968	74	251
Jan. 1, 1969	76	305
April 1, 1969	88	376
July 1, 1969	100	418

As the laboratory staff grew the organization became more formal. The organization of the main divisions and sections, as of April 1969, is shown in the chart in Fig. 1.

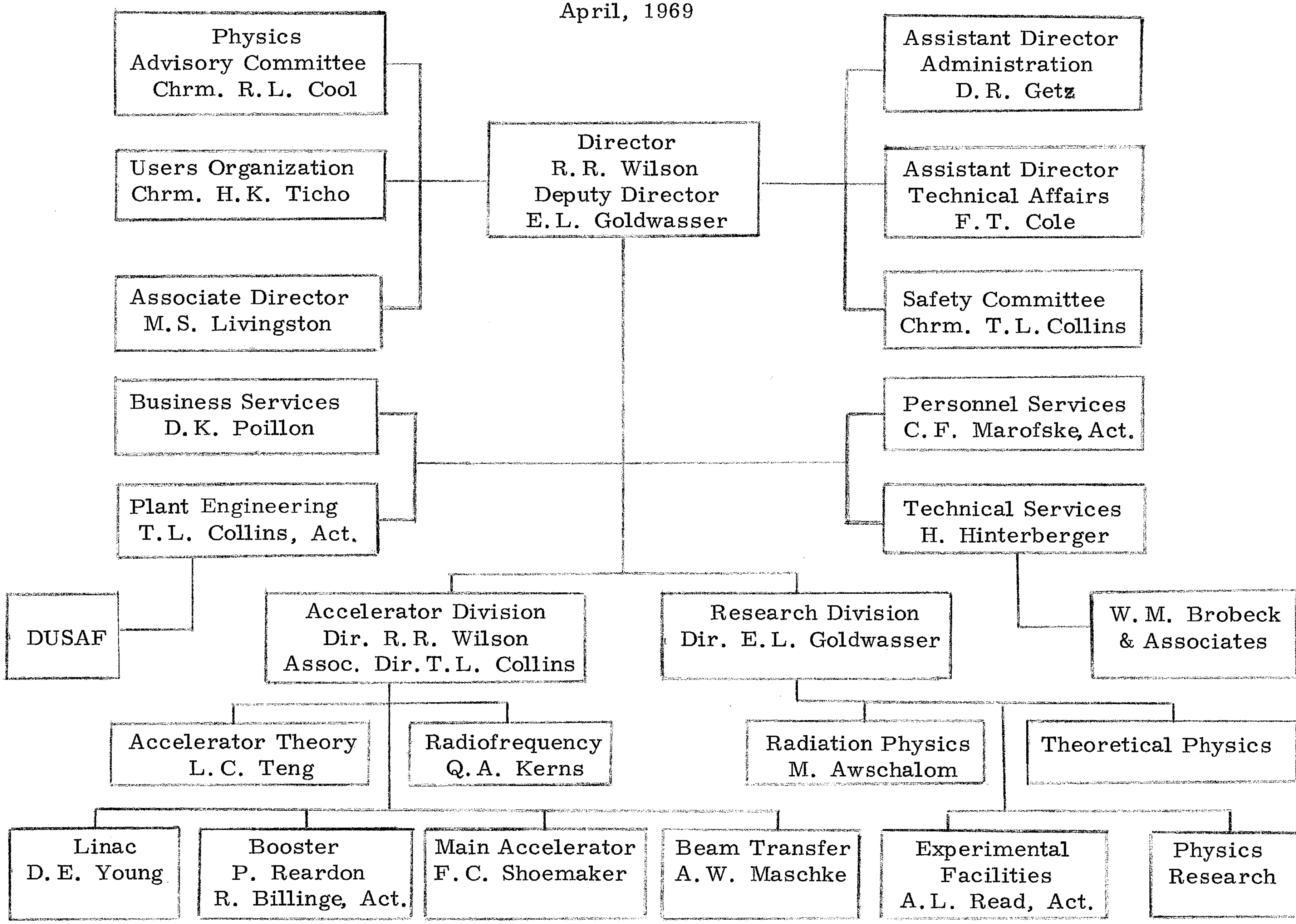
2. Laboratory Village and Site Procurement

Officials of the State of Illinois Department of Business and Economic Development started in 1967 the process of assessing land values and acquiring property on the 6800-acre site offered by the State to the U. S. Atomic Energy Commission as a site for the 200-GeV laboratory. The first part of the site on which purchase proceedings were started was the village of Weston, consisting of about 100 small houses on about 40 acres near the eastern boundary. An agreement was reached between State, AEC, and URA officials to turn over individual plots in the village to the NAL as they were acquired and vacated, for occupancy and use as design quarters.

The first NAL staff to occupy houses in the village was the Linac Section, in November 1967. F. T. Cole, Assistant Director, was made responsible for planning the move to the site and supervising the modification and construction program. As other plots and houses in Weston

Fig. 1

National Accelerator Laboratory
Organization
April, 1969



became available they were assigned to other groups of NAL staff. The Business Office staff moved in March 1968. The process of acquiring houses and transferring staff continued for another six months. During the summer of 1968 the village services were gradually turned over to the NAL. Official transfer to the State of the major block of houses owned by the Federal Savings and Loan Insurance Corporation occurred on August 1. The Oak Brook quarters were evacuated and the final moves to the site completed by October 1. By this time a general consensus developed for calling this design site the laboratory "Village."

A temporary laboratory building (Lab #1) for experimental use by the Linac Section was essentially completed and installation of equipment was started in April 1968. A second laboratory building, of the air-inflatable type, was occupied by the Main-Ring Section in April. A third, of steel construction, was turned over to the Radio-Frequency and Booster Sections in August. In November the village management was taken over by the Business Office under D. K. Poillon. The last residents moved out of the Village by December 15.

Contracts were placed in November and December for four additional laboratory buildings, of steel construction, assigned to the central Machine Shop and the Main-Accelerator, Booster, and Beam-Transfer Sections; these were occupied in May 1969. Prototype sections of the main-ring and booster enclosures of full-scale cross section were designed and built to house operating prototype units of magnets and other accelerator components. Several of the small village houses were moved to locations adjacent to the laboratories to provide office space and facilities, and plans were implemented to move houses to form a cluster around the Director's Office to provide a more efficient administrative center.

Acquisition of the major portion of the site by the State was started in August 1968. Surveying to locate the main ring and other components of the permanent installation was supervised by DUSAF. The first block of land to be transferred to the AEC, in November, was the Schimmelpfennig farm, on the site to be occupied by the permanent linac and booster buildings. A groundbreaking ceremony was held on the site of the linac building on December 1, at the time of start of construction by the contractor. The formal transfer of title of the entire site from the State of Illinois to the U. S. Atomic Energy Commission took place in Chicago on April 10, 1969.

The major construction contracts for buildings and facilities on the permanent site, negotiated and placed by DUSAF during FY 1969, include the following:

Nov. 22, 1968	-	Linac beam enclosure and equipment gallery
Dec. 6, 1968	-	Rough roads and grading
Feb. 26, 1969	-	Booster beam enclosure and equipment galleries
June 17, 1969	-	Cross gallery, Phase 1.

3. Site and Facilities Planning

February 1968 was named "architecture month," during which an intensive effort was made to establish the forms and arrangements of the major buildings on the permanent site, particularly in the area of the "footprint" consisting of the linac, booster, transfer hall to the main ring and the high-rise central office building. A major result was the addition of the "cross gallery" linking the linac, booster, and transfer hall. Access tunnels from the lower level of the cross gallery go to the linac, booster, and main-ring enclosures for use during installation and for maintenance operations. The cross gallery provides a ground-level space for delivery and assembly of equipment and also provides space and conduit connections for the central control station of the accelerator. This decision removed the central controls from the previously assigned location in a lower floor of the high-rise building and made it possible to defer many decisions on detailed design of the high-rise to a later date in the design and construction schedule.

Another activity during architecture month was to study and compare differing concepts for the high-rise central laboratory building. DUSAF representatives presented four basically different concepts, illustrated with models. The strong favorite of the NAL staff was a tapered cylindrical building with a hollow center and inner court. Modifications of this design have been used in subsequent site planning and modeling.

Another problem in building arrangements was the location of the linac enclosure relative to the other components of the "footprint." Compaction of space between these components was desirable to minimize distance and shorten lines of communication. For a time a "bent linac" was considered, having two straight sections at a 90° angle external to the high-rise building. This concept was dropped when the cross gallery was conceived, in favor of a straight linac enclosure as in the earlier planning, but displaced closer to the main-ring transfer hall. With this location, the linac beam run passed over the booster tunnel, under the booster gallery and was injected radially from inside the booster orbit. At a still later date, as indicated in a section to follow, the linac beam run was redesigned to be deflected outward around the booster enclosure and injected radially from outside the orbit.

Water conservation has required careful planning and negotiation with planning boards in the Fox River area and the State of Illinois Water Authority. Fox River water will be used only during the months of high flow. A large storage pond will be excavated on the site to provide water throughout the year. Rainwater runoff will be channeled and pumped to the storage pond. Local wells will be drilled for domestic water. Any effluent from the site back to the Fox River will be treated to avoid pollution.

Test drilling on the site of the main ring disclosed a layer of compact glacial till more suitable as a base for the main-ring tunnel slab than the clay loam nearer the surface. A decision was made in late 1968 to lower the floor of the main-ring tunnel by 2 1/2 feet below the initially-planned grade (to elevation 722.5) to utilize the till for the slab foundation.

With the reduced size of main-ring magnets and quadrupoles resulting from the magnet development program, the 12-ft expanded tunnel sections at the mini-straights (at 100-ft spacings) were eliminated and the normal 10-ft sections used.

4. Master Plan

During 1968-69 the DUSAF staff prepared several studies with increasing detail of a master plan for the NAL site. These were presented to the NAL Director and his staff for comments and modifications. The latest presentation, in March 1969, showed the following features and facilities:

a) Master Plan (general)
b) Utility distribution corridors
c) Master road plan
d) Industrial water (Fox River system)
e) Industrial water (surface drainage)
f) Industrial water (and fire protection) distribution
g) Domestic water system
h) Sanitary sewer system
i) Industrial waste collection system
j) Low conductivity water supply and return
k) Cooling ponds for LCW system
l) Gas distribution and supply system
m) Electrical power system
n) Communications
o) Fire zone designations.

C. ACCELERATOR COMPONENTS

1. Injection Into Main-Ring Long Straight Section

A significant change in orbit arrangement for the main ring followed a decision to inject the beam from the booster directly into the ejection long straight, rather than into a medium straight. This arose from detailed studies of the technique of vertical injection into the main ring. The advantage of vertical injection comes from the smaller vertical emittance of the beam from the booster and the small vertical dimensions of the magnets. It was found that the bending and septum magnets for vertical injection could be mounted at the entry end of the long straight section above the orbit, without interfering in any way with the kicker and septum magnets used for ejection in the radial plane. A considerable number of advantages followed from this change. The revisions were carried on in early 1968 and were incorporated in the revised descriptions and parameters listed in the second printing of the Design Report published in July 1968.[1a]

2. Revised Main-Ring Lattice

Removal of the injection function from the medium straight made it possible to reduce the length of the drift spaces of all six medium straights. In the revised lattice arrangement the first two bending magnets in the thirteenth cell of each superperiod are omitted to form a medium straight section, with a field-free drift space of about 49 ft. The two magnets omitted are of the B1 type with wide radial aperture.

Since the primary planned use of the medium straights is for beam clean-up targets, the large momentum dispersion at the location of the medium straight becomes an advantage. Transfer of the injection function into the long straight also removed the need for an injection straight section housing formerly planned for a medium straight, with significant reduction in estimated cost for the main-ring structures.

Associated with this revised lattice arrangement for the main ring was a change in the design of the quadrupole matching elements at the long straight sections. This change substituted sets of four quadrupoles of standard lengths at each end of the long straights in place of two quadrupoles of non-standard length, thus standardizing the physical dimensions of the quadrupoles used in the main ring. This revised magnet lattice for the main ring was reported by Garren at the 1969 Particle Accelerator Conference.[4]

3. Main-Ring Magnets

Progress in the design of main-ring bending magnets during 1968 came from a sequence of magnetic model studies to determine the precise shape of poles and from engineering studies of the support structures and techniques for assembly. Three successive short models of full-scale cross section were built and powered to make magnetic measurements. Laminations were stamped from seven different magnetic materials.[5] Experience was gained in the design and insulation of excitation coils, procured from several suppliers.

Two full-length bending-magnet cores were procured and tested to study rigidity and other mechanical properties when supported only at the ends. The first full-length core utilized a bolted-side-plate design with welded connectors; the second had channel girders over the top and bottom with welded ties on the sides between girders. Neither met the requirements fully and a third design was developed which promises to be the final design. In this final form four angle girders are machined to fit closely around the four corners and welded to the laminations so they become part of the magnetic return circuit. The weight of iron laminations was reduced and magnetic properties were improved with this change.

The quadrupole magnets have gone through a similar process of design development, aided by computer design of pole-tip shapes. A short-length working model of full cross section was built and magnetically tested. An improved design was developed in early 1969, with a 12-turn coil rather than a 17-turn coil, and with smaller external dimensions and weight of iron. Magnetic tests showed it to be superior.

4. Main-Ring Aperture Dimensions

The magnetic aperture of the main-ring magnets was chosen at an early stage in design, following analysis of many interrelated properties of the chosen magnet lattice. The significant factors considered in determining the vertical height of the magnet gap were:

a) magnitude (emittance) of betatron oscillations within the main-ring magnets, of the injected beam from the booster,

b) tolerances for imperfections and errors in design, fabrication and alignment of magnets in the main ring,

c) effect of space charge in blowing up beam dimensions, and

d) vacuum wall thickness.

Additional factors affecting the radial width of "good" field were:

e) beam width due to momentum spread at injection and transition,

f) sagitta of orbit arc in a straight magnet, and

g) beam oscillations during resonant beam extraction.

The factor which most critically affected the choice of vertical aperture was the effect of space charge (c); that for the radial aperture was space for beam oscillations during extraction (g). The apertures for the bending magnets given in the Design Report[1a] (as revised July 1968) were: B1: 5.0×1.5 inches, B2: 4.0×2.0 inches. These dimensions have been used in the magnet design and modeling programs.

A challenge to the choice of radial aperture arose in April 1969 and led to discussion and further studies to analyze the technical and economic factors involved. Bellendir and Teng[6] showed that magnet lattices could be devised to produce large values of the amplitude function β_x at the location of the septum used for extraction. This led to the possibility that use of high β_x at the septum could bring a decrease of radial amplitudes around the rest of the orbit during extraction and so reduce the allowance for (g) above. Also, Wilson suggested that the allowance for closed-orbit errors [(b) above] might be reduced or eliminated by using beam-position measurements taken during operation to guide the realignment or correction of magnets.

Cost reductions coming from reduction of aperture were estimated. They were found to be small for decrease of radial dimensions but significant for decrease of the magnet gap length. Reduction in aperture height was found to be undesirable due to its effect of decreasing the space charge limit (c), as well as requiring major redesign and model testing of magnets.

Courant[7] showed that use of high β_x at the septum would decrease the turn-to-turn separation Δx during resonant extraction which would decrease ejection efficiency. Reduction in radial aperture was found to decrease tolerances for magnet construction and installation. The beam width at transition energy due to momentum spread was analyzed and estimates made of this as a possible additional aperture requirement. Teng[8] summarized the review of main-ring apertures and concluded that the design dimensions should be retained.

5. Injection Accumulator

An alternative method of filling the main-accelerator ring would be to store successive pulses from the booster in an injection storage ring located in the main-ring tunnel, operating in the dc mode at the low field (486 gauss) required to store protons of booster output energy. This accumulator ring could be filled during the entire main-ring magnet excitation cycle (2.2 sec) and the accumulated beam injected into the main ring in one turn, thus eliminating the 0.8 sec filling time otherwise required for accumulation of injection pulses from the booster.

Potentially, this could result in shortening the time cycle and increasing the time-average intensity. The booster pulse repetition rate could be reduced from 15 Hz to, say, 5 Hz, which would reduce booster rf power requirements and cost. And the change in booster properties might result in other cost savings such as by a possible reduction in linac energy.

Similar schemes had been proposed by planners at an early stage of the conceptual design phase but were not actively pursued. The concept was revived by Wilson in early 1968 and became the subject of a sequence of group discussions and a series of comparative technical and cost analyses by the NAL staff.

Wilson[9] prepared a general study of the advantages of the proposed scheme, including simple designs for accumulator magnets. At the low fields required the magnets could be small, excited by single-turn conductors and supported from the roof of the main-accelerator tunnel. Shoemaker[10] studied the effect on the field in the accumulator magnets of stray magnetic fields from the pulsed main-ring magnets and bus bars, finding it large enough to require either special shielding or current programming in the accumulator. Billinge and van Steenbergen[11] studied the relative technical features of a booster operating at lower cycling rates and with 1-turn or 2-turn stacking in the accumulator ring. Billinge, Kerns, Teng, van Steenbergen and Young[12] analyzed the significance of a reduction in linac energy. Finally, Brobeck and

Associates[13] prepared a comparative cost estimate based on optimized parameters which showed that inclusion of an accumulator would probably not result in a reduction in total costs.

On the basis of these studies the decision was to reject the accumulator option for the initial construction plans. In addition to the cost, other reasons were the more stringent and exacting demands on the performance of extraction and beam-transfer systems and a possible reduction in reliability and performance of the main ring.

6. Booster Magnet and Vacuum-Chamber Modifications

A major revision in the design and dimensions of the booster magnet occurred in the summer and fall of 1968 which affected many auxiliary components and resulted in significant reductions in the cost estimates. The booster magnet described in the revised Design Report[1a] of July 1968 included AG magnets with central orbit pole gaps of 2.5 and 2.0 inches in the D and the F sectors and with 16×24 inches external dimensions. When a full-scale wood model was built and delivered at Oak Brook its size seemed excessive compared to models of main-ring bending magnets. Wilson instigated a restudy of all design features which could reduce the booster magnet size and cost.

The vacuum chamber for this fast-cycling magnet is a serious design problem, involving either ceramic or thin metal-wall chambers, for which an economical and suitable design had not yet been developed. A major change recommended by Wilson was to eliminate the vacuum chamber between poles and substitute an external vacuum sheathing outside the magnet as used with the Cornell electron synchrotron. Experience at Cornell suggested that acceptably low pressures during operation could be achieved within an external vacuum sheathing. This principle was accepted for the new design and plans were made for model studies to develop techniques for outgassing and pumping. An immediate consequence was reduction of the central orbit pole gaps to exclude space assigned to vacuum-chamber walls.

Steps were also taken to reduce the radial magnet apertures. A technique for assembling magnet laminations on a curved arc was developed to remove the requirement for sagitta of the orbit arc in a straight magnet. The tolerances assigned for imperfection and misalignment errors were restudied and reduced somewhat below the initial values. Snowdon restudied the pole face shape with more careful attention to edge shaping, resulting in computer-developed contours to provide "good" field over a wider fraction of the pole face. The result of these studies was a magnet of considerably smaller outside dimensions of 13×18 inches and with D and F central orbit pole gaps of 2.25 and 1.64 inches. The new design was reported at the 1969 National Accelerator Conference[14] in Washington.

The reduction in magnet size resulted in considerable reduction in estimated costs of iron. A major saving came from the change in vacuum-chamber technique. Magnetic stored energy was reduced from

1.2 megajoules to 0.8 megajoules with corresponding reductions in the ratings of power-supply components. Dimensions of chokes and capacitors in the resonant power supply became small enough so they could be mounted within the supporting box girders for the magnets in the tunnel. Power cabling was simplified and shortened, and above ground space in the booster power-supply building was reduced allowing this building to be reduced to about half the original dimensions.

7. Excitation of Booster Magnets

The powering system for the booster magnets consists of a distributed resonant circuit of inductors and capacitors which provides nearly sinusoidal excitation at 15 Hz frequency biased to vary between injection and ejection fields. The highest rate of change of field, and so the peak requirement for radio-frequency acceleration, occurs at about half the maximum magnetic field. A method of reducing the peak rf requirement, which would reduce rf-system costs, would be to shape the magnetic-field cycle to make the field rise more linearly. Such shaping can be approximated by adding a small component of second harmonic (30 Hz) in the resonant powering circuit for the magnet.

A circuit to accomplish this was described by Dinkel and Ryk[15] in a technical memorandum in August 1968 with a comparative cost estimate. G. F. Tool made an analysis of the reduced radio-frequency requirements and gave an estimate of cost savings. The net cost differential was less than $100,000. This was considered too small to justify the additional complexities so the use of harmonic excitation was discarded.

A significant change in the technical features of the power supply for booster magnet excitation was developed by Cassel and others in the Booster Section in early 1969. This change was to substitute a single SCR rectifier system for the dual power supply of ac and dc initially planned to produce the biased sinusoidal wave form. This "series pumping" circuit involves a special power transformer with two sets of windings connected to SCR rectifiers in "star" and "delta" respectively. Phase control of the SCR rectifiers in the two circuit components is used to develop the desired wave form. Comparative bidding on prototype units showed the new system to be significantly lower in cost.

8. Second Harmonic in Booster Radio Frequency

The addition of higher rf harmonics to the accelerating voltage in a synchrotron had been proposed and discussed before the NAL design study was started. The subject was discussed during the 1967 summer study at Oak Brook. P. Morton and R. Gram wrote a report[16] summarizing the potential advantages of using a set of second harmonic cavities in the booster. One purpose was to reduce the phase-oscillation frequency ν_s in order to minimize coupling to betatron oscillations and reduce the width of half-integral stopbands. Another was to reduce the Sørenssen space charge parameter η at transition energy where an increase in longitudinal phase space is most damaging. Use of the second harmonic at injection might also improve the trapping efficiency.

This topic was reopened in a concentrated study program called "Booster Second Harmonic Week," held during the week of November 11, 1968. About 15 members of the Booster and Theory Sections met for discussions and made analyses of the implications of adding a second harmonic. E. L. Hubbard circulated minutes of the meetings[17] to the participants.

Analysis showed that coupling to transverse oscillations would not be important if phase frequency were kept below $\nu_s = 0.1$ (design $\nu_s = 0.08$). Courant demonstrated that the η parameter, and hence the space-charge effect at transition, is not significantly reduced by the addition of a second harmonic. In general, none of the potential advantages was found important enough to justify the addition of a second harmonic system to the booster. The basic rf system projected in the Design Report was retained.

9. Repetition Rates of Booster and Main Ring

The repetition rate of 15 Hz for the booster and the magnet-pulsing time of the main ring of 2.2 sec (without flattop) were chosen at an early stage in design to be compatible with other parameters and are specified in the Design Report. In line with the general policy of examining critically all of the design parameters to identify possible technical improvements or economic savings, the Director appointed a task team to study the technical and economic features of alternate choices of these repetition rates. The task team consisted of Billinge, Collins, Kerns, Maschke, Shoemaker, and Teng. A report of the results of this study was presented by Teng in a laboratory note.[18]

It was known that reduction of either repetition rate would result in reduction of radio frequency and magnet power requirements with a consequent reduction in cost. The question was whether other technical and cost factors would override these savings.

In accordance with design performance specifications it was assumed that the average design beam current at 200 GeV should be 1.5×10^{13} p/sec and that the main ring should be capable of a duty factor of 25%. The injection energy for the booster of 200 MeV and the final booster energy of 10 GeV were taken as design figures; the orbit radii and beam apertures of the booster and main ring were taken as fixed.

For purposes of this study three values of booster repetition rate were chosen: 15 (design), 10, and 7.5 Hz; three values of main-ring pulsing cycle were used: 2.2 (design), 3.2, and 4.2 sec. This gave a matrix of nine combinations which were analyzed and cost estimated.

The most notable technical result was an increase in the required linac beam current for all cases of lower repetition rate. Although providing such an increase is technically feasible, it would result in larger output beam emittance and momentum spread from the linac and probably to larger beam losses in transport and injection into the booster.

Larger beam currents in the ring accelerators would approach space charge limits more closely, impose more critical tuning conditions and result in a somewhat reduced capability for a future increase in beam intensity. The reduced rate of rf acceleration with longer cycling times would result in larger momentum oscillations which are most critical at the transition point and could lead to increased beam blow-up factors and more critical controls. The longer flat-top required to produce 25% duty cycle would increase the already exacting demands on the precision of regulation of magnets during beam spill. So, reduced repetition rates were found undesirable on all counts relative to performance, beam quality, and eventual capability.

In the analysis of cost reductions the same unit costs were used as in the cost estimating for the Design Report. The major cost differentials were found to be in the radio-frequency systems and in the magnet power supplies for booster and main ring. Other cost effects were estimated but found to be considerably smaller and were not included. The resulting estimated reductions varied from \$0.4 million to \$1.1 million for the eight alternate choices. The maximum reduction of \$1.1 million was about 10% of the total costs of the components involved. No clear break point or optimum value was observed on plots of cost reductions vs repetition rate. No estimates could be made of the required additional manpower, effort, time, and cost for design revisions if specifications were to be changed; these costs might significantly reduce the apparent savings.

The conclusion from this study was that the cost savings using reduced repetition rates were too small to justify a change in these parameters at this stage of design and considering the significantly increased threats to accelerator performance and beam quality.

10. Reduction of Booster Energy

The booster maximum energy of 10 GeV for transfer into the main ring was chosen, rather arbitrarily, at an early phase of the design study in 1967. This "round number" was not seriously questioned as a design parameter until 1969. Then the task team consisting of Billinge, Collins, Kerns, Maschke, Shoemaker, and Teng studied the consequences of reducing booster energy to 8 GeV. The result was reported by Teng[19] in a laboratory note dated May 20, 1969. The study showed a decrease in estimated costs of the booster magnet power and radio-frequency systems and an increase for the main-ring radio-frequency system with a net reduction of about $450 K. The major effect on accelerator performance was a reduction (by 20%) of the beam space-charge limit in the main ring. Due to this threat to the ultimate machine intensity and concern over the uncertain costs of a redesign effort, the task team recommended that the transfer energy of 10 GeV be retained.

The Director was dissatisfied with the recommendation and called the task team together for further discussion. Technical arguments were reviewed and cost modifications reestimated. Other effects on machine performance were noted, particularly the improved performance of the booster at the reduced rating. The possibility of further reduction to 7 GeV was analyzed and discarded. The subject was discussed and the modified parameters were presented at a general staff meeting in early June 1969 where the Director made a decision to reduce the booster transfer energy to 8 GeV, and instructions were given to proceed with the necessary design modifications.

11. Revised Booster Injection System

An important change in the arrangements for injection of the linac beam into the booster was developed by the Booster group in early 1969 in time to modify construction drawings for the booster enclosure. The arrangement shown in the Design Report[1] included a linac beam run which crossed above the booster enclosure and under the booster gallery and was injected radially from inside the booster orbit.

In the rearrangement the linac beam is deflected outward, pitched down at about 13° to the level of the booster, transported for about 65 feet inside the booster housing, and injected radially into the booster orbit from the outside. A variety of simplifications and improvements resulted from this change. The relatively inaccessible "black hole" in the beam run crossing the booster enclosure was eliminated. The linac beam run is outside the booster for the entire length. The booster housing is enlarged to accommodate the beam-handling equipment along the run without reducing space for maintenance and handling. The beam run inside the booster enclosure is long enough to provide drift length for a debuncher in the linac beam, with readily accessible components.

12. Radio-Frequency System

Development of the radio-frequency systems for acceleration in the booster and in the main accelerator has, in most respects, followed the plans described in the Design Report.[1] Basic parameters have been modified slightly in response to revised requirements[20] and improved technical specifications of commercially available items.

One significant change in the fall of 1968 was the decision to locate the power amplifiers for the rf cavities of the main accelerator within the main-ring tunnel rather than in an above-ground power amplifier building at the rf straight section. This change came when it was realized that the cavity-power-amplifier systems for the main ring were quite similar to those for the booster. A single design was developed with the power amplifier tube mounted directly over the cavity. The two systems differ somewhat in structural features of the cavities and also in the ferrite tuning elements which are closely attached to the cavities. This decision to locate the main-ring power amplifiers in the tunnel, as in the booster, eliminated the need for an external power building at the rf straight section. The remaining equipment building, which is outside the shielding, houses the low-level rf input circuits, the dc power supplies and the control components for the rf system.

13. Linac Progress

Development of the prototypes for the pre-accelerator and linac has proceeded according to plans and on schedule. No significant changes have been made in the basic designs reported in the Design Report.[1a] The Linac Section occupied the first laboratory building in the Village in April 1968. The 750 kilovolt high-voltage generator unit, obtained on loan from the Argonne National Laboratory, was installed in the pit of the laboratory building in December. A proton beam accelerated to 60 keV was achieved in the ion-source test stand on January 20, 1969. The pre-accelerator high-voltage generator with an accelerator column installed was tested to 780 kV in March. A 600-keV proton beam was achieved on April 17 and tuned-up to 750 keV at a beam current of 70 milliamps before the end of the month. The 25-ft tank for the first 10-MeV section of the linac was delivered in February; cleaning, testing, and installation of drift tubes proceeded through May. The first accelerated beam of 10-MeV protons was expected in June 1969.

14. Radiation Control

The policy for control and shielding of radiation has been restudied and calculations based on it have been used to specify shielding requirements for each component of the accelerator. The basic approach is described in the revised Design Report.[1a] The most significant difference from policies and shielding specifications in earlier accelerators is the enhanced significance of the residual radioactivity arising from beam spills. There is a practical limit to the allowable intensity of residual activity, based on the necessity of limiting the exposure of maintenance and development personnel during essential activities. This allowable limit specifies the maximum intensity of beam spill, averaged over some effective time of operation and so sets a practical limit to the beam intensity which can be accelerated. Beam intensities will be increased above this limit only as the ability to control and limit the beam spills improves.

The three facets of the radiation problem--shielding, residual radioactivity, and radiation damage to materials--are all proportional to the amount of beam power lost in spills. The 200-GeV accelerator will have a total beam power about 200 times greater (480 kW) than earlier proton accelerators. However, the percentage beam spill will be much smaller for several reasons. No internal targets will be used, and the septum for the emergent beam is designed for extremely small losses (< 0.1%). Gas scattering losses around the orbit (at 1×10^{-7} torr) will also be less than 0.1%. Beam clean-up targets will be located in several medium straights. Instead of beam losses being distributed around the orbit, as in earlier accelerators, the losses in the 200-GeV orbit will be confined to a relatively few points where spills can be controlled by local shielding.

The allowable maximum intensity of residual activity is determined from analyses of time requirements for maintenance activities and from the maximum permissible dose (MPD) established by Federal agencies for radiation workers. The residual activity dose rate after accelerator turn-off is taken from measurements at CERN and BNL as a function of beam loss power and time following turn-off. From this the allowable beam power in the spill, and so the allowable beam intensity, can be determined.

This maximum allowable beam spill power at any location determines the intensity of radiation at this location during operations and so establishes the source intensity for calculation of shielding thickness around the enclosure. Each proton in the spill undergoes nuclear interactions with material in its path and produces a large number of secondary particles and radiations, mostly projected downstream. The transverse attenuation of these secondaries is dominated by the fast neutron component for which the characteristic nuclear interaction distance is about 120 g/cm^2, nearly independent of the material. The minimum shield thickness around the "quiet" portions of the orbit (magnet sectors) is based on an average spill loss of 0.1% around the orbit, multiplied by 10 as a safety factor. Shield thickness for other locations (ejection septum, injection straight, beam clean-up targets in medium straights, etc.) is based on the design losses at each location, multiplied by 10 as a safety factor. The bulk of the shielding material is earth-fill around the enclosures and can be extended in the future as required.

A variety of special radiation problems require special analysis and treatment. Penetrations through lateral shields for vehicle and personnel entry have been designed following the results of calculations and measurements on labyrinths of varying design. Lateral shielding along the linac is tapered in several steps determined by the increasing beam energy and anticipated beam spill power. Beam dumps for the linac and booster, to be used during tuneup or abort operations, have been analyzed and specified. The highest intensity radiation will be produced at the emergent proton beam targets and dumps. For these areas remote handling will be essential. Present concepts involve a movable car on rails carrying the target, analyzing and focusing magnets and other components which is placed within a concrete blockhouse with earth overfill for shielding and which can be towed to a cooling-off area following use. All components used in such high-radiation areas will be designed for maximum radiation resistance.

D. PLANNING FOR EXPERIMENTAL USE

1. Aspen Summer Study 1968

The conceptual planning of the facilities to be provided for experimental use of the accelerator is the responsibility of the Experimental-Facilities Section of the Research Division. In this planning, scientists active in high-energy physics who are potential users of the NAL have been invited to participate. A major concentration of effort occurred in a summer study held at Aspen, Colorado, from June 17 to August 17, 1968.

A total of 72 experimental and theoretical high-energy physicists attended, as well as 8 members of the NAL staff. Many important topics were discussed and a large number of valuable reports were written. The study was so successful that a similar study is planned for summer 1969.

Among the topics discussed were the optimum size of the research program, the number of target stations and secondary beams, and the relative balance between the several categories of experimental techniques. The discussions affected major laboratory decisions such as the internal target station, scope of the bubble-chamber program, and the potential future need for storage rings. Many of the reports considered typical experiments and the equipment required to perform them.

Concepts developed during the summer were studied in more detail by the Experimental-Facilities Section during the following year. By April 1969 a pattern emerged which justified a request to the AEC for authorization to proceed with Title I design of the experimental areas.

2. Removal of Internal Target Facility

A change in the Experimental Facilities planning which was stimulated by discussions at the Aspen Summer Study 1968 was the removal from the main ring of the internal target experimental area described in the Design Report.[1] The arguments and studies leading to this decision are summarized in a laboratory report.[21]

Internal targets are used in other accelerators where emergent beams have not been available and have been found advantageous for experiments in which multiple traversals of a thin target can increase the yield of secondaries. The inclusion of an internal target facility in the early planning at NAL seems to have been based on previous experience of the lengthy development times required in some earlier accelerators to obtain suitable emergent beams. The need should not be essential at the NAL where the emergent beam is expected to be immediately available.

At Aspen, Maschke presented several arguments showing the disadvantages of an internal target to the utilization and maintenance of the accelerator. Wattenberg considered a range of experiments in which thin targets and multiple traversals might be advantageous and found reasons in each case to show that they could be performed equally well in an emergent beam. General discussion showed no examples of any experiments in which the internal target was a specific requirement. A decision was made to remove the internal target area from the site planning and to apply the equivalent in funds to expanding the emergent beam experimental areas.

3. Bubble-Chamber Program

Considerable discussion at the summer study was concerned with the usefulness of the bubble chamber as an experimental tool in the very high energy range. Studies showed that bubble chambers will still be useful for strong-interaction experiments up to about 70 GeV. However, their major usefulness will be for the study of weak interactions, primarily those produced by neutrinos. The recommendations from the summer study were that a large liquid-hydrogen bubble chamber should be planned as a major experimental facility in a high-intensity, well-shielded neutrino beam.

During the following year several avenues were explored to determine the availability of existing or planned bubble chambers at other laboratories or the possibility of arranging for financial support of a new chamber for NAL. A 7-ft chamber with a cryogenic magnetic field under construction at Brookhaven National Laboratory was designed as a prototype for a future 14-ft chamber planned for the AGS. The possibility of diverting the 14-ft chamber to NAL on completion was discussed, including initial use of the 7-ft at NAL. A reappraisal of this plan was required by failure to obtain approval for the BNL plan in the FY 1969 budget. Another potential source was the 12-ft cryogenic chamber under construction at the Argonne National Laboratory. The diversion of this chamber to NAL after one or two years of operation at ANL was also discussed. However, neither plan would provide a chamber as large as seemed required or having the proper aspect ratio to utilize effectively the higher energy at NAL.

A third plan, started early in 1968 and discussed at the summer study, was a proposal[22] from Brookhaven to design a 25-ft cryogenic chamber at BNL specifically to meet the needs of the NAL, to be a joint project of Brookhaven and NAL, and to be built and installed at NAL by Brookhaven staff. This plan met with general favor and became the basis for a joint proposal to the AEC for funds to construct such a 25-ft chamber. If authorized in FY-70, it could be in operation by 1975.

4. Experimental-Area Concepts

The continuing studies resulted by April 1969 in a significant improvement in the arrangement of the beam runs and target stations in the experimental area.

Three target stations are provided in the rearrangement. Beams can be switched between successive target stations or shared between them if desired. The emergent beam line runs approximately 1350 feet in an underground tunnel from the ejection straight section to the first switching station. Here the beam is split with part or all of it going straight ahead to the first target station (1). The remainder of the proton beam is deflected in the switching station by an angle of 7.5° in the direction of curvature of the main ring; it travels approximately 1350 feet to the second switching station. Here the beam can be switched or split again, either traveling straight on to a second target station (2), or deflected through a second angle of 7.5° and directed toward a third target station (3). The advantage of this arrangement over that described in the Design Report is that the directions of successive beam runs diverge, providing increasing separations between experimental areas as distance from the targets increases.

This arrangement providing three target stations fulfills the scope of the authorized design proposal as described in the Design Report. Additional beam runs, switching stations, and target stations can be added in the future by extension of this initial arrangement.

The straight-through beam at the first switch point leads to the first target station, 1. The first target and the experimental-area arrangement beyond it has as a primary purpose the production of a neutrino beam, directed into a large liquid-hydrogen bubble chamber for the study of neutrino-produced weak interactions. For this purpose a beam run of nearly 2000 ft is provided beyond the target for mesons to decay and produce neutrinos, followed by a shield of as yet unspecified material of about 1000-ft length to absorb muons and to the bubble chamber beyond the shield. A secondary beam of K and π mesons emerging from the target at an upward angle of about 25 mrad will be collimated and run through deflection magnets and a radio-frequency velocity separator to produce an 80 GeV/c beam. This secondary meson beam will run parallel to and 20 ft above the neutrino beam axis. Beyond the muon shield the meson beam will be deflected down to the level of the bubble chamber for the study of fast interactions.

The second target station, 2, will be located in the straight-through beam run beyond the second switch point. Beyond the target a collimator with up to 6 diverging channels at small angles will provide beams of secondary radiations to experimental areas for a variety of electronic-type experiments of more-or-less conventional type.

The third target station, 3, will be located in the deflected beam beyond the second switch point. Details of the facility are as yet unspecified; it is intended to supplement target station 2.

The general arrangement described above has been adopted for purposes of site planning, and the DUSAF architect-engineers are developing details of roads, utilities, and other service features. Detailed planning of targets, shielding designs, and experimental areas continues.

5. Storage-Ring Design Study

In response to a request from the High Energy Physics Advisory Panel of the AEC, laboratory staff members prepared a design study on a future storage-ring facility for the NAL. A report[23] was published in booklet form in the fall of 1968. Such a study of storage-ring options at the 200-GeV accelerator was desired as a guide to long-term planning within the AEC. In preparing the report, it was assumed that it would be some years before such a storage-ring project would be authorized, so the report was not a proposal for construction; rather, it was a feasibility study based on present technology with a realistic cost estimate which can be used as a guide for future planning.

Earlier concepts of a colliding-beam facility at the NAL are described in the initial Design Report,[1] based on the use of a beam bypass in which a stored beam in an auxiliary, tangential storage ring would be arranged to interact with a stored beam in the main-accelerator ring. This scheme was reevaluated and discarded during the 1968 study. The primary reason was to avoid the operational disadvantage of tying up the main ring during stored-beam experiments.

In the study, the importance of equal beam energies in p-p interactions was emphasized so the center-of-mass of the interaction would be at rest within the laboratory. A basic arrangement was chosen of two intersecting storage rings in which beams circulate in opposite directions, with six beam crossings; two crossings would be used for injection of beams and four for beam-beam interactions. A minimum beam energy of 100-100 GeV was chosen to make the results scientifically interesting. At a magnetic field of 20 kilogauss, which can be achieved with conventional iron-copper magnets, the overall size would be about one-third of the main ring, a radius of 333 meters.

The use of superconducting or cryogenically cooled magnets is expected in the future to reduce the very large power requirements of conventional dc magnets. High-field superconducting magnets could also reduce orbit radius, for a given energy, with potential overall cost savings. This possibility was investigated. It was found that the technology of high-field superconducting magnets was not sufficiently advanced at the present time to allow the preparation of responsible cost estimates. In order to obtain a cost estimate for future planning, the study group decided to base the design on the use of iron-cored magnets at 20 kilogauss field for which the orbit radius is that given above of 333 meters. Possible future development of superconducting magnets to higher fields would, for the same geometry, allow proportionately higher beam energies which would more fully exploit the potential of the accelerator.

Three types of excitation coils to excite the magnets to 20 kilogauss were considered:

a) conventional water-cooled copper; 35° C; 25.4 MW,

b) cryogenically cooled pure aluminum; 16° K; power 178.0 kW,

c) superconducting Nb-Ti coil; 4.2° K; power 8.0 kW.

Cost estimates for the three types were developed, including varying amounts for iron and power supplies, and shown to be essentially the same within errors of estimating. The major result of the study was that a 100-100 GeV facility could be built for approximately $75 million (in 1968 dollars).

In an Appendix, preliminary designs and tentative cost estimates were presented for high-field superconducting magnets (40 and 60 kilogauss) for 100-100 GeV accelerators of smaller radii, based on present technology and prices. These tentative cost estimates are somewhat higher than those for the 20-kilogauss design. However, it is considered possible that 60- or even 80-kilogauss superconducting magnets will be technically and economically feasible at the time a NAL storage-ring project starts.

REFERENCES

1. Design Report, National Accelerator Laboratory, January 1968; (a) Design Report, National Accelerator Laboratory, revised second printing, July 1968.
2. M. S. Livingston, Early History of the 200-GeV Accelerator, National Accelerator Laboratory NAL-12, June 18, 1968.
3. F. T. Cole, Monthly Report of Activities, National Accelerator Laboratory NAL-14, Aug. 1, 1968, etc.
4. A. A. Garren, Lattice of the NAL 200-GeV Proton Synchrotron, 1969 Particle Accelerator Conference, Washington D. C., March 5-7, 1969.
5. R. Yamada, Iron Evaluation Tests for Main-Ring Magnet, National Accelerator Laboratory Internal Report TM-171, May 6, 1969.
6. J. Bellendir and L. C. Teng, High-β Modification of Main Ring Long Straight Section, National Accelerator Laboratory FN-189, May 21, 1969.
7. E. D. Courant, The Effect of a High-Beta Insertion on Resonant Extraction, National Accelerator Laboratory Internal Report TM-163, April 11, 1969.
8. L. C. Teng, Review of the Main-Ring Apertures, National Accelerator Laboratory Internal Report TM-166, April 24, 1969.
9. R. R. Wilson, Injection Accumulator NAL Proton Synchrotron, National Accelerator Laboratory NAL-11, May 13, 1968.

10. F. C. Shoemaker, Effect of Pulsed Stray Magnetic Fields on the Injection Storage Ring, National Accelerator Laboratory FN-138, April 25, 1968.

11. A. van Steenbergen and R. Billinge, Booster Parameters for 1- or 2-Turn Stacking in the Accumulator, National Accelerator Laboratory FN-148, May 15, 1968.

12. R. Billinge, Q. Kerns, L. Teng, G. Tool, A. van Steenbergen, and D. Young, Injection Energy of the 5 Hz Booster, National Accelerator Laboratory FN-147, May 8, 1968.

13. W. Brobeck & Associates, Storage Ring Cost Estimate, April 17, 1968.

14. R. Billinge, S. C. Snowdon, and A. van Steenbergen, Design of NAL Booster, 1969 Particle Accelerator Conference, Washington, D. C., March 5-7, 1969.

15. J. Dinkel and J. Ryk, Second Harmonic in Booster Magnet Current, National Accelerator Laboratory Internal Report TM-23, Aug. 29, 1968.

16. R. Gram and P. Morton, Advantages of a Set of Second Harmonic Cavities, National Accelerator Laboratory FN-108, Nov. 1, 1967.

17. E. L. Hubbard, Minutes of Booster Second Harmonic Week Meetings, Nov. 11, 15, 1968.

18. L. C. Teng, Repetition Rates of Booster and Main Ring, National Accelerator Laboratory FN-181, March 11, 1969.

19. L. C. Teng, Effects of Reducing the Transfer Energy from 10 BeV to 8 BeV, National Accelerator Laboratory FN-188, May 20, 1969.

20. J. A. Dinkel, Q. A. Kerns, L. A. Klaisner, and G. S. Tool, NAL Booster and Storage Ring RF Systems, 1969 Particle Accelerator Conference, Washington, D. C., March 5-7, 1969.

21. A. W. Maschke, A. Wattenberg, and D. H. White, Considerations on an Internal Target Facility, National Accelerator Laboratory Internal Report TM-76, July 12, 1968.

22. 25-Ft Cryogenic Bubble Chamber Proposal, Brookhaven National Laboratory BNL-12400, March 1969.

23. Proton-Proton Colliding-Beam Storage Rings for the National Accelerator Laboratory, Design Study 1968.